

Toxicity of Combustion Products from Burning Polymers: Development and Evaluation of Methods

by P. L. Wright* and C. H. Adams†

Laboratory and room-scale experiments were conducted with natural and synthetic polymers: cotton, paper, wood, wool, acetate, acrylic, nylon, and urethane. Smoke and off-gases from single materials were generated in a dual-compartment 110-liter exposure chamber. Multicomponent, composite fuel loads were burned within a 100 m³ facility subdivided into rooms. In chamber experiments, mortality depended on the amount of material burned, i.e., fuel consumption (FC). Conventional dose (FC)/mortality curves were obtained, and the amount of fuel required to produce 50% mortality (FC₅₀) was calculated. With simple flame ignition, cotton was the only material that produced smoke concentrations lethal to rats; FC₅₀ values for cotton ranged from 2 g to 9 g, depending on the configuration of the cotton sample burned. When supplemental conductive heat was added to flame ignition, the following FC₅₀ values were obtained; nylon, 7 g; acrylic, 8 g; newsprint, 9 g; cotton, 10 g; and wood, 11 g. Mortality resulting from any given material depended upon the specific conditions employed for its thermal decomposition. Toxicity of off-gasses from pyrolysis of phosphorus-containing trimethylol propane-polyurethane foams was markedly decreased by addition of a flame ignition source. Further studies are needed to determine the possible relevance of single-material laboratory scale smoke toxicity experiments. Room-scale burns were conducted to assess the relative contributions of single materials to toxicity of smoke produced by a multicomponent self-perpetuating fire. Preliminary results suggest that this approach permits a realistic evaluation of the contribution of single materials to the toxicity of smoke from residential fires.

Introduction

Concern over the potential toxicity of smoke produced when materials burn in residential or institutional fires has increased in the recent past. Particular concern has been expressed regarding possible unusual toxic effects of combustion products from synthetic materials. This concern has been evidenced in statements in building codes, petitions to the Consumer Product Safety Commission, and increased private and public research. Major publicity has been given to a relatively small number of bench-scale experiments demonstrating the toxicity of smoke produced when single materials were pyrolyzed. Less emphasis has been given to statistics demonstrating the steady decline in fire-

related mortalities in the United States, (Fig. 1). The rate in 1955, excluding the estimate for

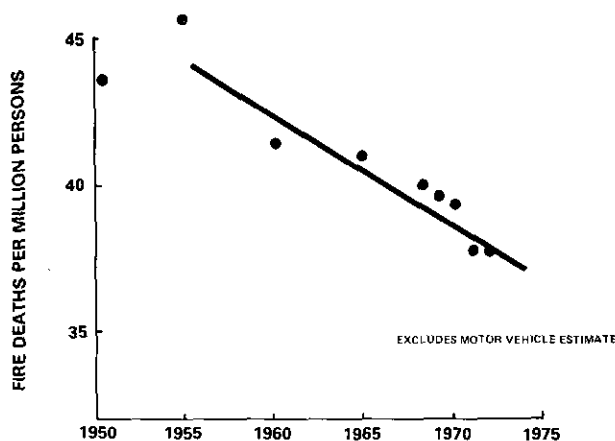


FIGURE 1. U.S. annual fire-related death statistics.

* Department of Medicine and Environmental Health, Monsanto Company, St. Louis, Mo. 63166.

† Fire Safety Center, Monsanto Company, St. Louis, Mo. 63166.

motor vehicle-related mortalities, was over 46 per million persons (1). In 1974, it was approximately 37 per million. From these statistics, it is very difficult to conclude that there has been an increase in the relative toxicity of smoke in residential fires which paralleled the increased use of synthetic polymers during that 20-year period. Despite the absence of evidence of a contribution of synthetic polymers to an increased real life hazard from smoke, it is important that the relative toxicity of combustion products of all materials be known. In fully developed residential fires resulting in fatalities, more than one material is consumed. Therefore, the need exists for methods to assess the contribution of individual materials to the biological effect produced by smoke from a self-perpetuating multicomponent fire.

Materials

Rigid polyurethane foam samples (Table 1) were prepared by blending the polyol, phos-

Table 1. Rigid polyurethane foam formulations.

Component	Formulation		
	A (wt %)	B (wt %)	C (wt %)
Polyol	37.5 ^a	38.5 ^b	35.4 ^b
Amine	1.3 ^c	1.1 ^c	0.4 ^d
Silicone	0.5 ^e	0.4 ^e	0.5 ^f
Fluorocarbon		17.1 ^g	14.2 ^g
Isocyanate	50.2 ^h	42.9 ^h	49.1 ⁱ
Water	—	—	0.4

^a TP-340 (BASF/Wyandotte Corp.); hydroxyl number = 562.

^b Multanol 4034 (Mobay Chemical Co.); hydroxyl number = 470.

^c Triethylenediamine, Dabco LV-33 (Houdry Process and Chemical Co.)

^d Tetramethylbutanediamine, TMDBA (Union Carbide Corp.)

^e Silicone surfactant, L520 (Union Carbide Corp.)

^f Silicone surfactant, DC193 (Dow Corning Corp.)

^g Nias 11 (Union Carbide Corp.)

^h Papi 901 (Upjohn Co.)

ⁱ Polymeric isocyanate, Mondor MR (Mobay Chemical Co.; NCO equivalent weight = 133).

phorus additive, silicone, amine, and water for 30 sec at 2700 rpm. The fluorocarbon was then added, followed immediately by the isocyanurate. When the cream point was reached, the

mixture was poured into a 10 × 20 × 15 cm container. Samples (8 × 8 × 2.5 cm) weighing approximately 5 g were cut to fit the sample holder. All other natural and synthetic polymer samples were commercially available materials.

The composition of the composite fuel load is shown in Table 2. Each fuel load composite

Table 2. Composite fuel load composition.

Element ^a	Weight per composite, kg	Weight %	Element dimension, cm
Wood, fir ^b	8.2	50.0	4×4×50
Bolster	(8.2)	(50.0)	(10×14×50)
Cotton batting	2.9	18.8	4×14×50
Polyurethane	2.3	18.8	4×14×50
Cotton fabric	1.5	9.2	50×50
Paperboard	1.5	9.2	32×50

^a Complete fuel loads consisted of 20 wood elements and 25 composite bolsters.

^b After completion of the 30-min burn an average of 2.8 ± 0.5 kg charred wood remained.

consisted of 20 precut wood elements and 25 preformed bolsters. The bolsters contained cotton batting, flexible polyurethane, cotton fabric, and paperboard in the relative amount shown. Care was exercised in reproducibly placing the elements in the final configuration shown in Figure 2. This configuration was maintained by wire supports passed through holes in the ends of the wood elements at each of the four corners. The overall dimension of the fuel load was 50 × 50 × 70 cm. Materials were stored in an area at 22°C, 50% RH; the components contained approximately 5% moisture prior to combustion.

Experimental

Laboratory Scale

Experiments with rigid urethane foams were conducted in a National Bureau of Standards smoke density chamber following procedures described by Petajan et al. (2). Four male and four female Sprague-Dawley rats (225 g) were held in a wire cage with individual compartments, 12 × 10 × 12 cm. The bottom of the cage was 15 cm above the chamber floor. Total duration of animal exposure, including the 5-min sample decomposition time, was 20 min. Animals surviving the exposure were observed for a 14-day period, sacrificed, and autopsied.

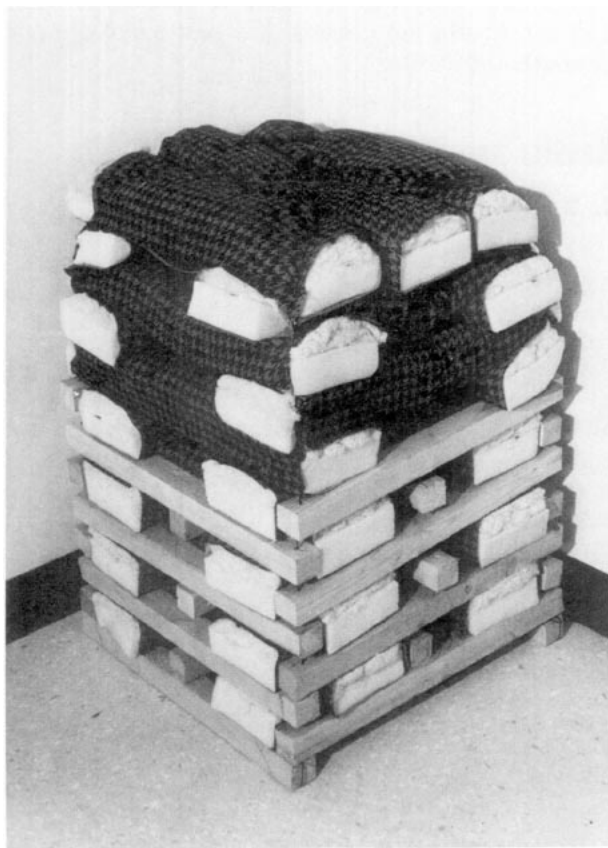


FIGURE 2. Composite fuel load used in room-scale experiments.

Experiments with other materials were conducted in a dual-compartment smoke generation and animal exposure chamber. The exposure chamber consisted of two separate stainless steel units coated on the inside with Teflon. These units ($30 \times 30 \times 60$ cm), placed 30 cm apart, were connected by 5-cm tubular ducts. The combined volume of the two compartments and ducts was 110 liters. The test material was combusted in the right-hand compartment and the animals were exposed in the left-hand compartment. A blower located on the top of the right chamber circulated gaseous combustion products at a rate of 200 l./min. To observe the exposure, removable safety glass view-ports were placed on the front of each compartment. Experiments were conducted under both simple ignition and forced combustion conditions.

In simple ignition experiments, a test polymer was suspended in a vertical position from a glass hanger located 5 cm from the top and 8 cm behind the front panel of the right compartment. The lower edge of the polymer was 2 cm above the flame source, which consisted of a horizontal butane torch regulated to give six 8-cm jets of flame spaced 2.5 cm apart. A 30-sec ignition time was used; no attempt was made to extinguish the polymer if it continued to burn after the torch was shut off.

In the forced combustion procedure, the horizontal torch was removed from the right compartment and replaced with an 8-cm diameter, 100-W surface heating element with external controls. Wood samples were cut into match-size pieces prior to combustion; other polymers were cut into 2.5-cm square pieces. The samples were held in a 1×10 cm stainless steel pan. Rats were placed in the left compartment and the chamber was purged with oxygen (1.5 l./min) for 5 min. Immediately prior to ignition, the sample was moved onto the preheated (300°C) heater. Ignition was accomplished with an 8 cm acetylene/air flame directed towards the surface of the sample for 30 sec. The oxygen purge and power to the conductive heater was continued until the samples ceased to flame or for a maximum of 5 minutes after ignition.

Following the 60-min exposure period, in the dual compartment chamber, surviving rats were transferred to standard laboratory cages and observed for 14 days prior to sacrifice and necropsy. A series of experiments utilizing increasing fuel loads was conducted with each material. The resulting fuel consumption and mortality data were used to calculate the fuel consumption that would result in death of 50% of the exposed rats by using a nonlinear regression equation [eq. (1)]:

$$Y = \frac{100(X/B)^4}{1 + (X/B)^4}$$

where Y = per cent mortality, X = grams fuel consumed, and B is the LD_{50} .

Room Scale

The experimental facilities (Fig. 3) consisted of three fire exposure rooms (areas 1, 2, and 4) connected by a corridor (area 3). These areas occupied approximately 40 m² of floor space and a volume of 100 m³. Systems for re-

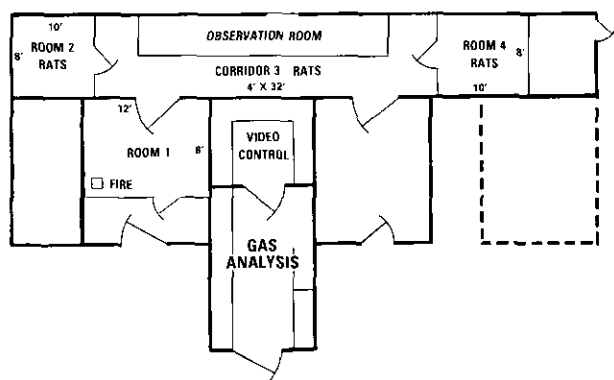


FIGURE 3. Experimental floor plan for room-scale facility.

mote visual, audio, and atmospheric monitoring were in an adjacent room. Room temperature was monitored by remote thermocouples. Oxygen concentration was determined by a paramagnetic procedure. Carbon dioxide and carbon monoxide were monitored by nondispersive infrared techniques. Nitrogen oxides were monitored by chemiluminescence and total hydrocarbons were determined by flame ionization (3). Hydrogen cyanide was trapped in caustic scrubbers and quantified colorimetrically (4). Gas concentration values were obtained from each location every 4.5 min. Integration of concentration/time plots provided cumulative exposure values to time of animal death and to completion of the 30-min experimental period.

The fuel load was placed on the floor in the corner of area 1 (Fig. 3) and ignited, after rats had been placed in the respective cages in areas 2, 3, and 4. Both 25-cm diameter motor-driven rotary cages (6 rpm) and stationary cages were located approximately 30 cm above the floor. Thermocouples and gas sampling lines were located adjacent to the animal cages. Male Sprague-Dawley rats weighing approximately 225 g were used in all experiments.

All exterior openings were closed during the burn, which lasted 30 min. The doorway leading from area 1 into the corridor was wide open during the burn. The door leading from the corridor into area 2 was partially closed with only a vertical opening of 650 cm² remaining. The door to area 4 was closed tightly, with only a horizontal opening of 100 cm² between the floor and the bottom of the door. The com-

posite fuel load was ignited at zero time with 100 ml of ethanol placed in a pan located 4 cm beneath the center.

Results and Discussion

Laboratory Scale

Early in 1974, the University of Utah Flammability Research Center reported a greater than expected toxicity from smoke from a foam containing trimethylol propane and phosphorus (2). A parallel series of tests were conducted to evaluate the effects of various phosphorus additives, foam compositions, and pyrolysis conditions. The additives tested included a brominated phosphate ester, a chlorinated phosphate ester, a polymeric chlorinated phosphonate, a reactive phosphonate, and an inorganic polyammonium phosphate. Foams were formulated to contain 16% by weight of each material. Those studies involved 35 separate exposures and 270 rats. Results of the first series of experiments with trimethylol propane foams (formulation A, Table 1) and pyrolytic decomposition are shown in Table 3. These results suggest a direct relationship between phosphorus content of the foam and the relative degree of toxicity of the smoke produced when pyrolytic conditions in the absence of pilot flame are employed. Mortalities occurred among rats exposed to smoke of each of these phosphorus-containing foams except the foam which contained less than 1% total phosphate.

Because it is highly improbable that a heat flux approaching 5 W/cm² radiant energy would ever occur in the absence of a flame, a series of experiments were conducted with the use of a pilot ignition flame. The samples were exposed to the 5 W/cm² radiant flux plus pilot ignition for 5 min. A marked reduction in the toxicity of the smoke produced from these trimethylol propane-containing foams, pyrolyzed in the presence of a pilot flame, was noted. In an additional limited number of experiments, no mortalities occurred among rats exposed to smoke produced from samples of the same foams decomposed by the pilot flame alone, in the absence of additional radiant energy.

In other experiments, the same phosphorus additives were used in foams that did not contain trimethylol propane (formulations B and C, Table 1). No deaths occurred among any of

Table 3. Acute toxicity of smoke from trimethylol propane-based rigid urethane foams containing phosphorus additives.

Additive ^a	Total phosphorus content, %	Combustion conditions ^b		Specimen consumed		Rat mortality ^c
		Radiant flux, W/cm ²	Ignition source	Wt, g	%	
None	0.0	5	None	2.9	52	0/8
None	0.0	5	None	3.0	53	0/8
None	0.0	5	Flame	5.1	93	0/8
Brominated phosphate ^d	0.8	5	None	4.3	77	0/8
Reactive phosphonate ^e	2.1	5	None	3.0	55	7/8
Reactive phosphonate ^e	2.1	5	Flame	5.0	100	0/8
Reactive phosphonate ^e	2.1	5	Flame	4.8	92	0/8
Chlorinated phosphonate ^f	2.6	5	None	4.1	72	8/8
Chlorinated phosphonate ^f	2.6	5*	None	4.1	61	8/8
Chlorinated phosphonate ^f	2.6	5	Flame	5.2	84	7/8
Chlorinated phosphonate ^f	2.6	5	Flame	4.8	81	8/8
Chlorinated phosphonate ^f	2.6	5	Flame	5.2	87	0/8
Chlorinated phosphonate ^f	2.6	5*	Flame	5.5	86	0/8
Chlorinated phosphonate ^f	2.6	5*	Flame	5.9	94	1/8
Chlorinated phosphonate ^f	2.6	5*	Flame	5.4	87	0/8
Chlorinated phosphate ^h	1.7	5	None	4.5	69	5/8
Chlorinated phosphate ^h	1.7	5	Flame	5.0	91	0/8
Ammonium phosphate ⁱ	5.1	5	None	3.7	59	8/8
Ammonium phosphate ⁱ	5.1	5	Flame	8.0	100	1/8
Ammonium phosphate ⁱ	5.1	5	Flame	5.6	88	1/8
Ammonium phosphate ⁱ	5.1	5*	Flame	4.9	78	0/8

^a The base foam, formulation A, contained 16% of the indicated additive.

^b Radiant flux and ignition source were activated for 5 min.

^c Four male and 4 female Sprague-Dawley rats were exposed in the NBS chamber for 20 min.

^d Tris(2,3-dibromopropyl) phosphate (Michigan Chemical Co.).

^e Diethyl bis(2-hydroxyethyl) aminomethyl phosphonate (Stauffer Chemical Co.).

^f Bis(2-chloroethyl) (1-hydroxyethyl) phosphonate, 2-chloroethyl (1-hydroxyethyl) phosphonate, 2-chloroethyl (2-chloroethyl) phosphonate (Monsanto Co.).

^g The sample holder was pushed away from the radiant heat source after 5 min.

^h 2,2-Bis(chloromethyl)-1,3-propanediol bis[bis(2-chloroethyl) phosphate] (Monsanto Co.).

ⁱ Inorganic ammonium polyphosphate (Monsanto Co.).

the rats exposed to smoke from these more conventional formulations (Table 4) even though high levels of phosphorus were added and no pilot ignition flame was used.

In a series of experiments with the dual-compartment chamber and the simple ignition source, cotton was the only material that produced smoke lethal to rats (Table 5). Under this same experimental condition the maximum amounts of the other fabrics that were consumed, did not produce smoke concentrations lethal to rats. With this experimental procedure, a flash of flame traveled across the cotton surface almost immediately upon ignition. This surface flame self-extinguished before the completion of the 30-sec. pilot ignition. A second

flame persisted along the bottom edge of the cotton for approximately 30 sec. after the ignition source was turned off. When the later flame self-extinguished, a glowing red line persisted across the bottom edge of the material, this smoldering combustion line slowly moved upward until the sample was consumed. Consumption of a 6 g cotton sample attained in approximately 20 min was 90%. The other materials melted and dripped, shrank away, or in the case of wool, formed a char.

With cotton, it was found that by varying the amount of fuel burned, it was possible to obtain a conventional exposure-response curve (Fig. 4). With the relationship of mortality to fuel consumption established, it was possible

Table 4. Acute toxicity of smoke from sucrose-based rigid urethane foams containing phosphorus additives pyrolyzed in the absence of flame.

Additive ^a	Formulation	Total phosphorus, %	Specimen consumed ^b		Rat mortality ^c
			Wt, g	%	
None	B	0.0	3.9	56	0/8
None	C	0.0	3.5	56	0/8
Brominated phosphate ^d	B	0.8	7.0	72	0/8
Reactive phosphonate ^e	B	2.1	4.1	93	0/8
Reactive phosphonate ^e	C	2.2	3.6	58	0/8
Chlorinated phosphonate ^f	B	2.6	4.8	70	0/8
Chlorinated phosphonate ^f	C	2.8	6.1	76	0/8
	B	1.8	5.5	69	0/8
	C	1.9	4.0	64	0/8
Ammonium phosphate ^g	B	4.7	4.6	59	0/8
Ammonium phosphate	C	5.2	3.0	50	0/8

^a Either formulation contained 16% of the indicated additive.

^b Radiant flux (5 W/cm²) was activated for 5 min, no pilot ignition.

^c Four male and 4 female Sprague-Dawley rats were exposed in the NBS chamber for 20 min.

^d Tris(2,3-dibromopropyl) phosphate (Michigan Chemical Co.).

^e Diethyl bis(2-hydroxyethyl) aminomethyl phosphonate (Stauffer Chemical Co.).

^f Bis(2-chloroethyl) (1-hydroxyethyl) phosphonate, 2-chloroethyl (1-hydroxyethyl) phosphonate, 2-chloroethyl (2-chloroethyl) phosphonate (Monsanto Co.).

^g 2,2-Bis(chloromethyl)-1,3-propanediol bis[bis(2-chloroethyl) phosphate] (Monsanto Co.).

^h Inorganic ammonium polyphosphate (Monsanto Co.).

to calculate FC₅₀, the fuel consumption required to result in 50% mortality. When a single piece of cotton material was suspended vertically, the FC₅₀ was approximately 2 g (Table 6). When two pieces were suspended vertically, the FC₅₀ increased to approximately 5 g. Cotton

fabric piled loosely on a screen and ignited resulted in an FC₅₀ of 8.9 g. These different configurations resulted in increasingly persistent flaming and accelerated rates of fuel consumption. As a result of the variation in characteristics of the experimental fire, differ-

Table 5. Acute toxicity of smoke from simple ignition experiments with commercial fabrics in a dual-compartment chamber.

Specimen	Specimen consumed ^a		Rat mortality ^b
	Wt, g	%	
Cotton	5.6	88	5/6
Bleached	5.8	92	6/6
Sized	4.8	62	0/4
Acetate	4.8	62	0/4
Acrylic	1.6	29	0/4
Polyester	1.4	26	0/4
Wool	<1	<16	0/4

^a Represents the maximum fuel consumption obtained for each material under this test procedure.

^b Male Sprague-Dawley rats were exposed in the chamber for 60 min. Data indicate mortality/exposed.

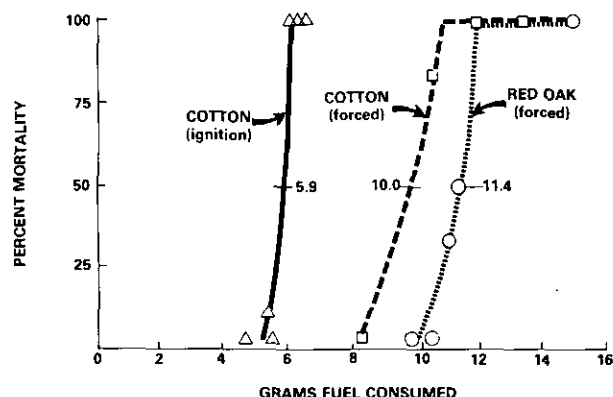


FIGURE 4. Effect of quantitative fuel consumption and combustion conditions on mortality of rats exposed to combustion products.

Table 6. Effect of sample configuration on the acute toxicity of smoke from cotton in simple ignition experiments.

Sample configuration	Experimental points ^a	FC ₅₀ , g ^b
Single, vertical	4	2.03
Double, vertical	4	5.05
Double, vertical	4	4.96
Double, vertical	5	5.30
Double, vertical	6	5.94
Horizontal, heap	5	8.94

^a Number of experiments conducted with each configuration; six male Sprague-Dawley rats were exposed for 60 min. in each experiment.

^b Calculated fuel consumption required to result in in death of 50% of the exposed rats.

ent estimates of smoke toxicity of the same material were obtained. Reproducibility of this method was evaluated in experiments utilizing the double vertical configuration. The variation among FC₅₀ values obtained with this configuration was well within that observed for acute oral LD₅₀ value determinations with a given material. A forced combustion method allowed consumption of adequately large amounts of several other materials to enable calculation of FC₅₀ values. Results shown (Table 7) are typical of those obtained with a

Table 7. Acute toxicity of smoke from forced combustion experiments with commercial materials in a dual-compartment chamber.

Specimen	Experimental points ^a	FC ₅₀ , g ^b
Acrylic	4	8.22
Cotton		
Bleached	4	10.00
Sized	4	9.89
Newsprint	3	9.10
Nylon	4	6.81
Wood, red oak	4	11.40

^a Number of experiments conducted with each material; six male Sprague-Dawley rats were exposed for 60 min. in each experiment.

^b Calculated fuel consumption required to result in in death of 50% of the exposed rats.

series of commercial materials. The range of results obtained with these materials, under the experimental condition employed, is consid-

erally less than the fivefold range obtained with cotton under varying experimental conditions.

Comparisons of the biological effects of smoke produced by various materials are confounded by the interaction of a material's physiochemical properties and the decomposition technique selected. Thus, the utility of any procedure employed to assess the biological effects of smoke is limited to the range of actual fire conditions the experimental technique represents. With a bench-scale chamber and single-component fuel load, it would appear that the most relevant technique used was that employing pilot ignition alone. This might be representative of the initial stage of fire when an ignition source comes in contact with a single item in a room. Methods employing high radiant flux from an electrical source simulates only similar conditions in a room situation, i.e., conditions where a material is exposed to a heated surface, which by itself does not contribute to biologically intolerable temperatures or gases in the room environment. This experimental condition is not representative of a developing room fire. Further studies are needed to determine the relevance of laboratory-scale combustion product toxicity experiments with single materials.

Room Scale

Nine replicate experiments were conducted to establish procedures and define the reproducibility of test methods and animal response. In these replicate experiments, all the animals in the corridor died during the exposure. Average time to death was 15.7 ± 3.0 min. Animals in rotary cages in area 2 also died within the 30-min exposure. Average time to death was 26.5 ± 4.1 min. Rats in the stationary cages in area 2 and all rats in area 4 survived the 30-min exposure and the subsequent 14-day observation.

Maximum temperature and gas concentration values, prior to animal death, are shown in Table 8. From single point values, it is not possible to reach meaningful interpretations of the relative importance of the individual factors. Single interval analytical values fail to reflect either the total cumulative exposure or rate of concentration change occurring prior to or following the determined value. Manifestations of toxicity following exposures to noxious gases are dependent upon both the con-

Table 8. Maximum exposure conditions prior to time of death of rats in room-scale tests.^a

	Room 3	Room 2	Room 4
Time to deaths, min	15.7 ± 3.0	26.5 ± 4.1	>30
Temperature, °F	193 ± 26	109 ± 7	86 ± 10
Carbon monoxide, ppm	5900 ± 1480	4900 ± 2060	2030 ± 630
Carbon dioxide, %	5.3 ± 1.5	6.5 ± 1.2	2.1 ± 0.4
Oxygen, %	13.8 ± 1.5	14.7 ± 2.1	18.8 ± 0.5
Hydrocarbons, ppm	150 ± 53	130 ± 68	60 ± 32
Nitrogen oxide, ppm	330 ± 120	160 ± 34	60 ± 7

^a All values mean ± standard deviation.Table 9. Integrated exposure prior to time of death of rats in room-scale tests.^a

	Room 3	Room 2	Room 4
Time to deaths, min	15.7 ± 3	26.5 ± 4.1	>30
Temperature, °F-75	1260 ± 290	570 ± 210	280 ± 190
Carbon monoxide, %	5.21 ± 1.7	6.05 ± 1.9	2.80 ± 0.6
Carbon dioxide, %	82 ± 26	98 ± 44	38 ± 8
Oxygen depletion, %-21	89 ± 32	134 ± 58	35 ± 10
Hydrocarbons, ppm	1160 ± 470	1540 ± 740	760 ± 360
Nitrogen oxides, ppm	3400 ± 1120	2700 ± 750	1400 ± 260
Hydrogen cyanide, ppm	180 ± 70	120 ± 50	60 ± 28

^a All values mean ± standard deviation.Table 10. Integrated exposure after 30 min in room-scale tests.^a

	Room 3	Room 2	Room 4
Temperature, °F-75	2540 ± 410	660 ± 250	280 ± 190
Carbon monoxide, %	13.39 ± 2.8	7.75 ± 2.8	2.80 ± 0.6
Carbon dioxide, %	160 ± 29	120 ± 39	38 ± 8
Oxygen depletion, %-21	176 ± 39	140 ± 45	35 ± 10
Hydrocarbons, ppm	3260 ± 1170	1840 ± 720	760 ± 360
Nitrogen oxides, ppm	5430 ± 915	3280 ± 350	1400 ± 260
Hydrogen cyanide, ppm	184 ± 71	120 ± 50	60 ± 28

^a All values mean ± standard deviation.

centration of the gas and the duration of exposure. The integrated exposures to time of death (Table 9) and to 30 min (Table 10) for each of the variables are indicative of the cumulative stresses the animals were subjected to during the experiment. The survival time for animals in areas 2 and 3 were inversely

proportional to the cumulative exposures of each of the variables monitored.

To determine the relative importance of the various stresses upon time to death, a series of linear multiregression analyses were fit to the data. Time to death of the animals in the rotary cages in areas 2 and 3 was considered

to be the dependent variable. The independent variables, though highly interrelated, were the integrated values for temperature and individual gas exposures prior to time of death. The only statistically significant ($p < 0.01$) coefficient was that for the temperature effect; the variation in temperature accounted for 68% of the variation in time to death. In experiments such as these, where the so called independent variables are so highly correlated, it is impossible to accurately determine their individual importance in affecting the dependent variable. Experiments with specific synthetic gas mixtures and controlled temperature stress will be required to determine the contribution of these individual factors on loss of biological integrity. However, these experimental results, utilizing a room scale facility and multi-component fuel loads, support the conclusion (5) that carbon monoxide and thermal exposure are the factors generally responsible for human fatalities following exposure to fires.

Recognizing the limitation of laboratory-scale experiments, it is readily apparent that the room-scale model more closely simulates actual fire situations in which materials are burning in one room and the victims are overcome in a distant room. The composite fuel load, based upon available information from the National Bureau of Standards and other sources, was selected to represent the composition of furnishings within a recreational or living room. This composite does not include components of construction, such as wood paneling or wall paper, nor does it include floor covering components. The concept allows the substitutions of individual materials into the fuel load for the materials that each would normally replace. For instance, rayon upholstery fabric could be substituted for a portion of the cotton fabric; a urethane foam containing flame retardant could be substituted for a

regular foam. Other modifications in the composite fuel load could include substitutions to incorporate wall, ceiling or floor construction materials.

The results of these experiments demonstrate that the substrate configuration and methodology influence the results obtained in laboratory-scale experiments. Techniques to extrapolate the results of laboratory experiments to actual fire conditions have not been demonstrated. The results of preliminary experimentation with a multicomponent fuel load in a room-scale model suggest that this is an approach to realistic evaluation of the contribution of individual materials to the toxicity of combustion products from a fully developed, unwanted fire.

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